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DEBUNCHING STUDIES AT ENERGIES CLOSE TO TRANSITION

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Abstract

A very-low-intensity bunch of protons in the Fermilab Main Ring was brought to an energy close to but below transition (frequency-dispersion factor $\eta_0 \gtrsim -2\times 10^{-5}$) at a front porch. The rf was turned off abruptly. The debunching was recorded in multi-trace oscillograms ("mountain-range plots") with $\sim$20 ms delay between traces. The front-porch energy was increased in very small steps in subsequent cycles to about $\eta_0 \simeq 8\times 10^{-5}$ above transition and the debunching repeated. The transition gamma could be determined very accurately by comparing the debunching rates at different energies. We observed longitudinal spread at every energy, indicating the presence of nonlinear effects in the frequency dispersion. The second term in the momentum-offset expansion of the momentum compaction, namely α_1, was determined.

1 Experimental Procedure

The experiment was carried out using a dedicated 2E cycle of the Fermilab Main Ring. A front porch of about 0.5 sec duration was set up in the magnet ramp close to the transition momentum of about 17.67 GeV/c, The beam was held in stationary rf buckets during this time.

To measure the fractional momentum spread $\delta = \Delta p/p$ of the bunch at the front porch, flying wires had been used. These consist of two flying wires in the horizontal plane at two locations of the Main Ring where the horizontal dispersions are different and nonzero. Each wire is a single 25-μ carbon filament mounted on a low moment-of-inertia fork, and is made to fly through the beam transversely at a constant speed of about 5 m/s. Knowing the lattice and dispersions at the wire locations, the beam emittance and momentum spread can be determined. One-booster-turn injection with 84 bunches was used in order to have enough intensity for the flying-wire measurements. Achieving more intensity by using more booster turns was not desirable, because the initial longitudinal emittance would have been larger. It was found that the minimum beam intensity for good wire profiles was 1×10^{11} particles. Constrained by the desire to keep the voltage and ramp curves for each front-porch momentum as close as possible, a lot of effort in tuning was required.

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Debunching studies followed after the flying-wire measurements. Here we reduced the number of bunches to 9 in order to have as small an intensity as possible to avoid rebunching due to beam loading when the rf was switched off. Approximately 0.2 sec after the start of the front porch, the rf voltage was turned off abruptly and the beam started to debunch. The whole debunching was recorded in the form of mountain-range plots at various intervals. Two broadband beam pickups were used. The first was a 3 GHz bandwidth coaxial 12.5 ohm beam pickup (stripline), and the other was a 6 GHz bandwidth wall-current monitor. The response of the stripline pickup to a delta-function excitation has been shown to be essentially a triangle with full base width of 300 ps, and the response of the wall-current monitor is expected to be a triangle with half of the former base. The signals from the beam pickups were transmitted through 200 ft of foam heliax cable to a Tektronix 7104 oscilloscope with a 1 GHz plug-in. The mountain-range displays were generated by adding the beam-current signal to a slowly increasing voltage ramp. The resulting signal was displayed on an oscilloscope triggered synchronously with the accelerator rf. Multiple triggers every 940 turns apart made it possible to put 5 traces on the screen of the scope, to be digitized off-line (Fig. 1). The effect of beam loading was checked by looking at the 53 MHz rf component of the Main Ring beam power as a function of time after the the rf drive was turned off. No significant beam-loading voltage was observed.

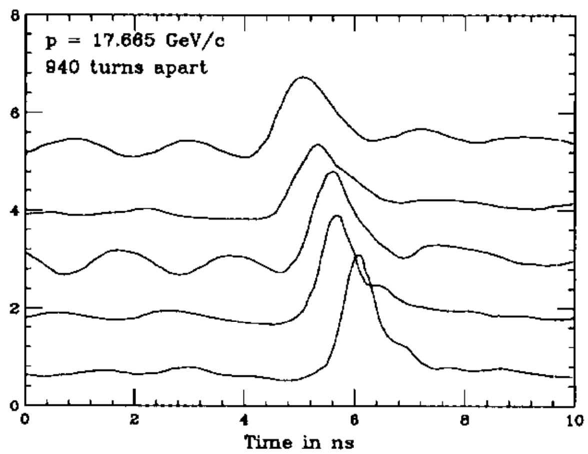

Fig. 1. Digitized mountain-range traces separated by 940 turns at front-porch momentum 17.665 GeV/c.

2 Debunching Rate and Determination of γ_t

The debunching measurements had been performed for momenta 17.58 Gev/c to 17.95 GeV/c, corresponding to frequency-dispersion factor

$$\eta_0 = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \qquad (2.1)$$

from roughly -2.9×10^{-5} to $+8.7 \times 10^{-5}$, where γ_t is the transition γ and was believed to be roughly 18.7.

The analysis was performed as follows. For a digitized picture, a baseline was introduced for each mountain-range trace in order to eliminate the oscillatory signals which might have originated from the pickup stripline or monitor. Then the *full* width of the longitudinal bunch length was determined. A special procedure was designed to eliminate the unwanted shoulder on the right side of the bunch profile, which was believed to be a result of instrumentation. The *full* width of the first trace, supposedly at the time when the rf was turned off, was subtracted to get the growth in bunch length. The debunching rate $\Delta T/T$ was derived from dividing this growth by the debunching time, and an average was obtained from the computation using the other traces of the picture and also other pictures at the same momentum. The debunching rates for all the momenta are plotted in Fig. 2.

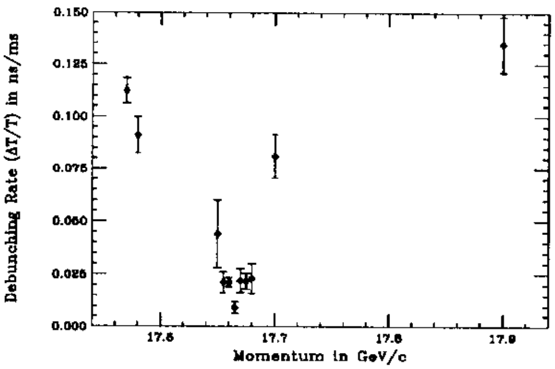

Fig. 2. Debunching rates versus front-porch momentum.

In the longitudinal phase space, we draw a curve encircling the spread of the bunch. A particle on this curve having reduced fractional momentum offset x (which ranges between ± 1) will spread out in the longitudinal direction according to

$$y(t) = y_0 + \eta_0 \delta x t + \eta_1 \delta^2 x^2 t \qquad (2.2)$$

after time t, where y_0 is the value of y at zero time,

$$\eta_1 \approx \alpha_0 \left(\alpha_1 + \frac{3}{2} \right) - \frac{3}{2}\eta_0 - \alpha_0 \eta_0 \;, \qquad (2.3)$$

and δ is the half maximum fractional momentum spread. In the above, use has been made of the expansion of the momentum-compaction factor,

$$\alpha = \alpha_0 (1 + \alpha_1 \delta) + \mathcal{O}(\delta^2) \;, \qquad (2.4)$$

with $\alpha_0 = \gamma_t^{-2}$. In the absence of the nonlinear term, or $\eta_1 = 0$, we expect no bunch-length increase right at transition; i.e., $\Delta T/T = 0$. The fact that the $\Delta T/T$ plot dips down to a nonzero minimum implies that the nonlinear term is not zero. From the plot, we can give an accurate determination of the transition momentum as 17.665 ± 0.002 GeV/c, corresponding to $\gamma_t = 18.853 \pm 0.002$.

3 Debunching at γ_t and Determination of α_1

Denote the longitudinal extent of the bunch edge in the longitudinal phase space by y and the *reduced* fractional momentum spread by x. The equation of the edge of a parabolic bunch at the start of rf shutdown is

$$x^2 + \frac{y_0^2}{\sigma_0^2} = 1 \;, \qquad (3.1)$$

where σ_0 is the half bunch length. Using Eq. (2.2), we obtain the shape of the bunch in the longitudinal phase space at time t as

$$x^2 + \frac{(y - \eta_0 \delta x t - \eta_1 \delta^2 x^2 t)^2}{\sigma_0^2} = 1 \;, \qquad (3.2)$$

or

$$y = \eta_0 \delta x t + \eta_1 \delta^2 x^2 t \pm \sigma \sqrt{1 - \frac{x^2}{\delta^2}} \;, \qquad (3.3)$$

where the plus (minus) sign is for the front (back) of the bunch. In the mountain-range plot, the projection onto the y-axis is measured. This corresponds to the extrema of y in the longitudinal phase space.

If the front-porch momentum is right at transition, the η_0 term in Eq.(3.3) drops out. Equating dy/dx to zero, we obtain two solutions for the extrema. When $\sigma_0/(2\eta_1\delta^2 t) > 1$, we have

$$y_{\mathrm{min}} = -\sigma_0 \;, \qquad y_{\mathrm{max}} = +\sigma_0 \;, \qquad (3.4)$$

and for $\sigma_0/(2\eta_1\delta^2 t) < 1$,

$$y_{\mathrm{min}} = -\sigma_0 \;, \qquad y_{\mathrm{max}} = \eta_1 \delta^2 t + \frac{\sigma_0^2}{4\eta_1 \delta^2 t} \;. \qquad (3.5)$$

This implies that for a short time after the shutdown of the rf, the bunch length stays apparently unchanged at $\pm\sigma_0$ in the mountain-range plot, and only when $t > \sigma_0/(2\eta_1\delta^2)$, the front of the bunch lengthens according to Eq. (3.5) to

$$y_{\mathrm{max}} = \eta_1 \delta^2 t + \frac{\sigma_0}{4\eta_1 \delta^2 t} \;. \qquad (3.6)$$

A schematic drawing of the debunching is shown in Fig. 3. Then we can solve for

$$\eta_1 \delta^2 = \frac{\sigma_0}{2t} \left[\frac{y_{\mathrm{max}}}{\sigma_0} + \sqrt{\frac{y_{\mathrm{max}}^2}{\sigma_0^2} - 1} \right] \;, \qquad (3.7)$$

with the total bunch length given by $y_{\max}+\sigma_0$.

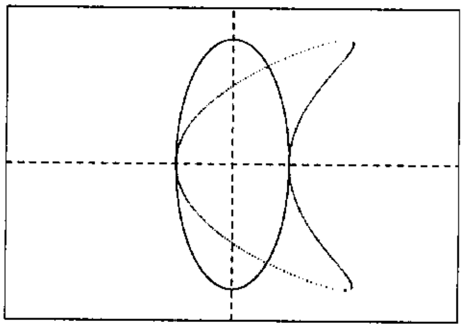

Fig. 3. A bunch in the longitudinal phase space right at transition, showing bunch shapes at shutdown of rf (solid) and after debunching for some time (dots).

The mountain-range plots shown in Fig. 1 at $p =$ 17.665 GeV/c or $\gamma = 18.854$ (right at transition) were analyzed carefully. The measurements are listed in Table I. The revolution period of the Main Ring is 20.9 μs, and the mountain traces are separated by 940 turns.

Table I: Debunching at transition.

Debunching Time (ms)	Total Bunch Width (ns)	$2\eta_1\delta^2 t/\sigma_0$	$\eta_1\delta^2$ $(\times 10^{-8})$
4×19.7	1.96	3.91	1.58
3×19.7	1.70	3.00	1.62
2×19.7	1.43	2.00	1.62
1×19.7	1.27	< 1	–
0	1.27	< 1	–

The results agree very well with our prediction, giving an average $\eta_1\delta^2$ of 1.60×10^{-8}. We analysed another set of data at $p = 17.665$ GeV/c and got an average $\eta_1\delta^2 = 1.63 \times 10^{-8}$. We did the same analysis at $p = 17.660$ and 17.670 GeV/c and got average $\eta_1\delta^2 = 2.63 \times 10^{-8}$ and 2.62×10^{-8}, respectively, showing clearly that these were not the exact transition momentum and the η_0 term of Eq. (3.3) had a significant contribution.

Unfortunately, the flying wires had not been working satisfactorily all the time, and no accurate direct measurement of δ had been recorded at the momenta from 18.66 to 18.67 GeV/c. However, we do have wire measurements at some neighboring momenta. For example, the rms fractional momentum spread was $(0.70 \pm 0.04) \times 10^{-3}$ at $p = 17.65$ GeV/c, and $(0.80 \pm 0.07) \times 10^{-3}$ at $p = 17.55$ GeV/c. Also the bunch length at the shutdown of the rf at $p = 17.65$ GeV/c was roughly the same as in the $p = 17.66$ to 17.67 GeV/c measurements. Gerig and Ankenbrandt [1] had measured the momentum aperture of the Main Ring at injection and found half the beam loss occurred when the fractional momentum was at $\pm 2.2 \times 10^{-3}$. Kourbanis et al [2] measured the transition energies at radially offset beams by looking for minimum bunch-shape oscillations after transition. They reported that the beam momentum near transition could be varied by $\pm 2.7 \times 10^{-3}$ without any appreciable change in beam loss. This indicates that the momentum spread of the beam near or at transition was far from filling up the whole momentum aperture. In the present experiment, we did not see any beam loss at front porches near transition. As a result, we believe that at transition δ should be from 1.6×10^{-3}, taking 2.5 standard deviations, to 1.8×10^{-3}. Using an average value of $\eta_1\delta^2 = 1.62 \times 10^{-8}$ and using Eq. (2.3), we obtain the determination $\alpha_1 = 0.74$ to 0.27. These values of α_1 agree roughly with a former determination of $\sim 0.8 \pm 30\%$ by Kourbanis et al [2]. The error has been large because of the uncertainty in δ and the subtraction of 1.5 in the determination of α_1 [see Eq. (2.3)].

4 Discussions

(1) Debunching near transition is a very nice way to measure the transition gamma accurately. Here, we need only to measure the debunching rate.

(2) Debunching right at transition should also be an accurate way to measure α_1, because the effect of α_0 can be eliminated. Unfortunately, the flying wire failed at the critical moment of the measurement and we need to infer the momentum spread instead. Here, our determination was $\alpha_1 = 0.74$ to 0.27.

(3) We can also evaluate α_1 from debunching near transition. However, the total bunch length can no longer be used in the analysis. This is because the maximum and minimum spreads of the bunch occur when the momentum spread is near to its maximum and minimum; i.e., $x \approx \pm 1$ in Eq. (3.3). We can see easily that the η_1 term drops out when we compute the bunch length from $y_{\max}-y_{\min}$. What we need to analyse instead is the asymmetric rates of debunching separately for the head and tail of the bunch; or compute $y_{\max}+y_{\min}$ instead. However, the timing of each mountain-range trace jittered. This is because the trigger of each trace had no clock to lock onto once the rf was turned off. Thus, it was very difficult to separate the debunching of the head from that of the tail, making the analysis impossible.

References

[1] R. Gerig and C. Ankenbrandt, *Main Ring Momentum Acceptance at 8 GeV*, Fermilab Acc. Expt. 132, 1986.

[2] I. Kourbanis, J. MacLachlan, and K. Meisner, *Measurement of the Momentum Dependence of Orbit Length in the Main Ring*, Fermilab Acc. Expt. 172, 1991.